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Rice cultivar tolerance to preemergence- and postemergence-applied fluridone

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Abstract

Fluridone was registered for use in rice production in 2023, offering a new herbicide site of action for growers. However, little information is available on the degree of rice tolerance to this herbicide. Field experiments conducted in 2022 and replicated in 2023 near Colt, AR, evaluated the tolerance of 12 rice cultivars to fluridone, applied preemergence or at the 3-leaf growth stage, in separate experiments. Each experiment consisted of one cultivar. Fluridone rates included 0, 168 (1 × label rate), and 336 (2 × label rate) g ai ha^{-1} in all experiments. Visible injury varied between years in all experiments, likely due to different environmental conditions. In 2022, injury following preemergence applications of fluridone was below 25% across cultivars. In contrast, in 2023, injury ≥30% occurred to five cultivars, with a maximum of 58% observed for the cultivar 'DG263L'. In both years, only three cultivars exhibited injury ≥20% following fluridone applications at the 3-leaf stage. Fluridone negatively affected shoot density, groundcover, chlorophyll content, and days to 50% heading in most cultivars when applied preemergence. When fluridone was applied to 3-leaf rice, at least one of the variables evaluated was negatively affected in two and nine cultivars in 2022 and 2023, respectively. Grain yield reductions of at least 18% were observed from eight cultivars in 2022, and a grain yield decrease from 9% to 49% from eight cultivars occurred in 2023 in the preemergence experiments. Fluridone applied to rice at the 3-leaf stage did not cause a yield penalty to any cultivar in 2022, whereas in 2023, a yield loss occurred from eight cultivars. Yield loss from the DG263L cultivar occurred at the 1 × rate in both experiments, indicating that this cultivar appears to be sensitive to fluridone, regardless of the application timing. Based on these findings, fluridone tolerance is cultivar-dependent. Furthermore, preemergence applications of fluridone to rice should be avoided.

Introduction

Rice production in the United States is primarily led by Arkansas, which accounts for nearly half of the country's total rice output, totaling almost five billion kilograms in 2023 (USDA-NASS 2024). Within the state, long- and medium-grain cultivars comprised 86% and 14% of the total rice production in 2023, respectively. In 2023, 54% of the total rice acreage was planted with the long-grain hybrid cultivars RT 7521 FP, RT XP753, RT 7321 FP, and RT 7421 FP, while 8% was allocated to the long-grain pureline cultivar DG263L (Hardke 2023). Additionally, 4% of the acreage was planted with the long-grain pureline cultivar CLL16 and 10% with the medium-grain pureline cultivars Jupiter and Titan.

Weed competition stands as one of the main factors limiting rice production, often resulting in more than 50% yield reductions, depending on variables such as weed density, species present, and time of emergence (King et al. 2024; Maun and Barrett 1986; Ziska et al. 2015). For instance, a single Palmer amaranth [*Amaranthus palmeri* (S.) Watson] plant that emerges 1 wk before rice can reduce rice yield by 5% to 50% within 1.4 m to 0.4 m from the weed, respectively (King et al. 2024). Besides decreasing yield, weeds can cause economic losses by reducing land value, primarily due to the additional costs associated with weed management and reduction in grain quality (Oerke 2006). Thus, effective weed control programs are essential for successful rice cultivation (Riar and Norsworthy 2011). Not surprisingly, herbicides are the most used pesticides in rice production in the United States, applied to 96% of the rice acreage (USDA-NASS 2022).

Varying degrees of herbicide tolerance have been documented among cultivars within the same crop (Beesinger et al. 2022; Bond and Walker 2011, 2012; Griffin and Baker 1990; Hardcastle 1979; Montgomery et al. 2014; Wright et al. 2021). For instance, hybrid and inbred,

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medium-grain rice cultivars were injured more than inbred, long-grain cultivars following a postemergence application of saflufenacil or carfentrazone (Montgomery et al. 2014). Wright et al. (2021) observed that long-grain and medium-grain pureline cultivars exhibited greater tolerance to florpyrauxifen-benzyl than a long-grain hybrid, which suffered a yield penalty when sequential applications of the herbicide were used. Additionally, rice tolerance to herbicides depends on the crop growth stage at the time of application (Bond and Walker 2011, 2012; Wright et al. 2021). Therefore, it is crucial to assess crop tolerance to new herbicides across cultivars at multiple application timings to identify risks associated with potential crop injury and yield loss.

Fluridone is an inhibitor of phytoene desaturase, a crucial enzyme in the biosynthesis of carotenoids (Bartels and Watson 1978; Sandmann and Böger 1997; Sandmann et al. 1991). Fluridone was recently registered for use on rice starting at the 3-leaf rice stage. Fluridone offers a novel site of action in rice production, providing residual control for annual grass and broadleaf weeds (US EPA 2023). Fluridone has also been registered for use in cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea L.)* production, and has shown excellent control of Palmer amaranth (Grichar et al. 2020; Hill et al. 2016). With the increased adoption of furrow-irrigated rice in Arkansas (Hardke 2023), Palmer amaranth emerged as a problematic weed in rice fields due to the favorable environmental conditions created by the nonflooded system (Bagavathiannan et al. 2011; Butts et al. 2022). The intensified interference from Palmer amaranth in rice fields, coupled with limited chemical options for its control due to herbicide resistance, makes this weed particularly difficult to manage. Therefore, fluridone emerges as a fundamental tool for farmers to manage this troublesome weed.

Despite its promising results in controlling Palmer amaranth, few studies have been conducted to investigate rice tolerance to fluridone. Martin et al. (2018) observed 25% injury to rice 7 wk after treatment following a preemergence application of fluridone at 224 g ai ha^{-1} on silt loam soil in a paddy system. Similarly, fluridone applied at 170 g ai ha^{-1} on clay soil following precision-leveling in a furrow-irrigation system caused more than 25% rice injury between 8 and 12 wk after treatment when applied at the 3-leaf growth stage (Butts et al. 2024). In both studies, fluridone injury increased following irrigation initiation, likely due to greater herbicide availability.

Due to the limited effective options available, fluridone may become a significant herbicide in battling Palmer amaranth in rice systems, provided crop tolerance is acceptable. Little information is available regarding rice response to this herbicide. Further investigations are necessary to evaluate its safety across a range of rice cultivars at different application timings. Therefore, this study assessed the tolerance of 12 rice cultivars commonly grown in Arkansas to fluridone applied preemergence and at the 3-leaf growth stage in a paddy production system.

Materials and Methods

Experiment Setup

To determine the tolerance of rice to fluridone within each cultivar, preemergence and postemergence experiments were conducted by cultivar, totaling 24 experiments in 2022 and 22 in 2023. The goal was not to compare cultivars, but rather, to understand the response of each cultivar to fluridone. Cultivars were planted in independent strips and treatments were randomized within each cultivar. The experiments were organized as a randomized complete block design with four replications. All experiments were located at the Pine Tree Research Station, near Colt, AR (35.1242°N, 90.9306°W), on a Calhoun silt loam soil with 1.4% organic matter and pH of 8 and 8.1 in 2022 and 2023, respectively. Twelve rice cultivars were drill-seeded at 36, 52, and 72 seeds m^{-1} of row for hybrids, a pureline quizalofop-resistant cultivar, and all other pureline cultivars, respectively (Table 1). The cultivar Lynx was planted only in 2022 due to seed availability. Rice in the experiments was planted with a nine-row, small-plot drill at a 1.3-cm depth with 19 cm between rows on May 12, 2022, and April 11, 2023. The plots were 1.8 wide and 5.2 m long. The seedbed was prepared using conventional tillage in both years.

The preemergence experiments aimed to evaluate the tolerance of each rice cultivar to fluridone when applied preemergence, and the postemergence experiments focused on rice tolerance to fluridone applied at the 3-leaf growth stage. Applications were made across all cultivars on the same date. In the preemergence experiments, the herbicide was applied to the soil surface on the day of planting. In the postemergence experiments, fluridone was sprayed on June 6, 2022, and May 16, 2023. Treatments consisted of fluridone (Brake®; SePRO Corporation, Carmel, IN) applied at 168 g ai ha^{-1} and at 336 g ai ha^{-1}, which corresponds to the 1 × and 2 × label rates for the soil texture in which the experiments were conducted (US EPA 2023). A “no fluridone” treatment was included for comparison, and all experiments were conducted under weed-free conditions to avoid interference from factors other than the treatments.

Weed control management was the same for all experiments each year. Quinclorac (Facet®L; BASF, Research Triangle Park, NC) was applied preemergence in both years. Postemergence herbicides were applied to 2-leaf rice in 2022 using halosulfuron-methyl + prosulfuron (Gambit®; Gowan Company, Yuma, AZ), while in 2023, propanil + thiobencarb (Ricebeaux®; UPL Limited, King of Prussia, PA) and halosulfuron-methyl (Permit®; Gowan Company) were used. The experiments were managed following University of Arkansas System Division of Agriculture recommendations for direct-seeded, delayed-flood rice production (Henry et al. 2021; Roberts et al. 2016). Flood establishment occurred 30 d after emergence, on June 18, 2022, and June 2, 2023, for all experiments. The herbicides were applied using a CO_2-pressurized backpack sprayer equipped with four AIXR 110015 nozzles (TeeJet Technologies, Glendale Heights, IL), calibrated to deliver 140 L ha^{-1} at a speed of 4.8 kph. Air temperature and rainfall data were monitored via a nearby weather station.

Visible crop injury was evaluated at 2, 4, and 6 wk after emergence (WAE) in the preemergence experiments and at 2, 4, and 6 wk after treatment (WAT) in the postemergence experiments using a scale of 0 to 100, with 0 representing no injury and 100 representing plant death (Frans et al. 1986). Rice shoot counts were taken in two 1-m sections of a row at 2 WAE in the preemergence experiments only, whereas all other subsequent variables were collected in both preemergence and postemergence experiments. Chlorophyll content was estimated using a soil plant analysis development (SPAD) chlorophyll meter (SPAD-502 plus Chlorophyll meter; Konica Minolta, Tokyo, Japan) at the rice panicle initiation growth stage, with readings of the uppermost fully expanded leaf of five plants per plot. A small, unmanned aerial system (DJI Mavic Air 2S; DJI Technology Co., Nanshan, Shenzhen, China) was used to capture aerial images from a height of approximately 60 m in 2022, with each image covering 12 plots

Table 1. List of rice cultivars, technology, seeding rate, description, and producer.[a]

Cultivar	Technology	Seeding rate	Description	Supplier[b]
		seeds m^{-1} of row		
CLL15	Clearfield	72	long-grain, pureline	Horizon Ag
CLL16	Clearfield	72	long-grain, pureline	Horizon Ag
DG263L	Conventional	72	long-grain, pureline	Nutrien Ag Solutions
Diamond	Conventional	72	long-grain, pureline	UADA
Jupiter	Conventional	72	medium-grain, pureline	UADA
Lynx	Conventional	72	medium-grain, pureline	UADA
Titan	Conventional	72	medium-grain, pureline	UADA
PVL02	Provisia	72	long-grain, pureline	Horizon Ag
RTv 7231 MA	MaxAce	52	long-grain, pureline	RiceTec
RT 7321 FP	FullPage	36	long-grain, hybrid	RiceTec
RT 7521 FP	FullPage	36	long-grain, hybrid	RiceTec
XP 753	Conventional	36	long-grain, hybrid	RiceTec

[a]Abbreviation: UADA, University of Arkansas System Division of Agriculture.
[b]Supplier locations: Horizon Ag, LLC, Memphis, TN; Nutrien Ag Solutions, Inc., Saskatoon, SK, Canada; RiceTec, Inc., Alvin, TX; UADA, Stuttgart, AR.

Table 2. Rice cultivar injury as influenced by rate and evaluation timing interaction by year following preemergence applications of fluridone.[a, b, c, d]

		2022			2023		
Cultivar	Rate	2WAE	4WAE	6WAE	2WAE	4WAE	6WAE
	g ai ha^{-1}	%					
CLL15	168	10	7	4	4	3	47
	336	14	10	9	5	2	36
	P-value		0.2816			0.1791	
CLL16	168	11	11	2	1	3	11
	336	17	16	4	2	2	9
	P-value		0.6363			0.6508	
DG263L	168	6 b	6 b	3 c	14	15	50
	336	10 b	16 a	20 a	19	25	65
	P-value		**<0.0001**			0.7609	
Diamond	168	5	4	3	1	1	3
	336	11	12	9	6	2	13
	P-value		0.3283			0.2885	
Jupiter	168	9 b	8 b	4 c	3	3	2
	336	19 a	17 a	15 a	8	4	4
	P-value		**0.0109**			0.7410	
Lynx	168	11 b	12 b	4 c	–	–	–
	336	19 ab	16 b	22 a	–	–	–
	P-value		**<0.0001**				
PVL02	168	9 abc	6 bc	0 d	9	7	26
	336	15 a	11 ab	5 c	23	23	53
	P-value		**0.0007**			0.8038	
RT7321 FP	168	13 ab	11 b	5 c	37	42	42
	336	24 a	19 ab	18 ab	40	35	30
	P-value		**0.0033**			0.0925	
RT7521 FP	168	10 bc	8 c	1 d	23 a	11 b	4 c
	336	20 a	19 a	18 ab	37 a	31 a	24 a
	P-value		**<0.0001**			**0.0037**	
RTv7231 MA	168	5 bc	3 cd	1 d	3 b	3 b	3 b
	336	12 a	10 ab	9 ab	6 b	8 b	33 a
	P-value		**0.0209**			**<0.0001**	
Titan	168	5 ab	6 ab	3 b	0	1	1
	336	14 a	11 a	12 a	6	3	6
	P-value		**0.0309**			0.1972	
XP753	168	8 bc	2 cd	1 d	15 c	7 d	1 e
	336	20 a	16 ab	15 ab	30 b	27 b	49 a
	P-value		**0.0082**			**<0.0001**	

[a]Abbreviations: WAE, weeks after emergence.
[b]Bold P-values indicate significance at $\alpha = 0.05$.
[c]Means within a cultivar by year for the fluridone rate by evaluation timing interaction followed by the same letter are not different according to Tukey's HSD ($\alpha = 0.05$).
[d]Flood establishment occurred 4 wk after emergence in both years.

in width and four plots in length. In 2023, images were captured at approximately 30 m, covering nine plots in width and four plots in length. Images were taken at 8 WAE in both years. Overhead images were analyzed using Field Analyzer (Green Research Services, Fayetteville, AR) to determine the groundcover percentage for each plot by measuring green pixel counts. Days to 50% heading were recorded for each plot and reported relative to each control. Rough rice grain yield was harvested from the center four

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Table 3. Rice cultivar injury as influenced by the main effect rate by year following preemergence applications of fluridone.[a, b]

Cultivar	Rate	2022	2023
	g ai ha^{-1}	——— % ———	
CLL15	168	7	18
	336	11	14
	P-value	0.2378	0.7402
CLL16	168	8*	5
	336	12	4
	P-value	**0.0043**	0.4872
DG263L	168	5	26
	336	15	36
	P-value	**0.0308**	0.1342
Diamond	168	4*	2*
	336	11	7
	P-value	**0.0001**	**<0.0001**
Jupiter	168	7	3
	336	17	5
	P-value	**<0.0001**	0.1411
Lynx	168	9	–
	336	19	–
	P-value	**0.0056**	–
PVL02	168	5	14*
	336	10	33
	P-value	**0.0384**	**0.0215**
RT7321 FP	168	10	40
	336	20	35
	P-value	**0.0142**	0.5864
RT7521 FP	168	6	13
	336	19	31
	P-value	**0.0016**	**0.0193**
RTv7231 MA	168	5	3
	336	10	16
	P-value	**0.0009**	0.2989
Titan	168	5	1*
	336	12	5
	P-value	**0.0045**	**<0.0001**
XP753	168	4	8
	336	17	35
	P-value	**0.0008**	**<0.0001**

[a]Bold P=values indicate significance at α = 0.05 based on pairwise comparisons.
[b]An asterisk (*) indicates a difference between fluridone rate averaged over weeks after emergence within the same column for each cultivar by year when interaction is not present.

Table 4. Rice cultivar injury as influenced by the main effect application timing by year following preemergence applications of fluridone.[a,b,c,d,e]

	Application timing					
	2022			2023		
Cultivar	2WAE	4WAE	6WAE	2WAE	4WAE	6WAE
	——— % ———					
CLL15	12 a	9 ab	7 b	5 b	3 b	42 a
P-value		**0.0057**			**<0.0001**	
CLL16	14 a	14 a	3 b	2 b	3 b	10 a
P-value		**<0.0001**			**0.0006**	
DG263L	8	11	12	17 b	20 b	58 a
P-value		**<0.0001**			**<0.0001**	
Diamond	8	8	6	4 b	2 b	8 a
P-value		**0.05467**			**0.0022**	
Jupiter	14	13	10	6	4	3
P-value		**<0.0001**			0.9810	
Lynx	15	14	13	–	–	–
P-value		**<0.0001**				
PVL02	12	9	3	16 b	15 b	40 a
P-value		**<0.0001**			**<0.0001**	
RT7321 FP	19	15	12	39	39	36
P-value		<0.0001			0.5545	
RT7521 FP	15	14	10	30	21	14
P-value		**<0.0001**			**<0.0001**	
RTv7231 MA	9	7	5	5	6	18
P-value		**0.0006**			0.9137	
Titan	10	9	8	3	2	4
P-value		**0.0170**			0.7269	
XP753	14	9	8	23	17	25
P-value		**0.0003**			**<0.0001**	

[a]Abbreviation: WAE, weeks after emergence.
[b]Bold P-values indicate significance at α = 0.05.
[c]Means within the same row for each cultivar by year followed by the same letter are not different according to Tukey's HSD (α = 0.05).
[d]When interaction is present, means for the main effect evaluation timing is not separated by letters.
[e]Flood establishment occurred 4 WAE in both years.

rows of each plot using a small-plot combine, and grain moisture was adjusted to 12% when reporting yield.

Data Analysis

All data were analyzed using R statistical software version 4.2.2 (R Core Team 2023). All data were fitted to a generalized linear mixed-effect model (GLMM) (Stroup 2015) using the *glmmTMB* function within the GLMMTMB package (Brooks et al. 2017). Year was included in the model as a fixed effect, and block was treated as a random effect for the analysis of all variables. The interaction of year and fluridone rate was significant for most variables across cultivars (P > 0.05). Therefore, data were analyzed by year. Rice shoot density, chlorophyll content, groundcover, relative heading date, and yield were analyzed using a Gaussian or normal distribution. Percent visible rice injury was analyzed using a beta distribution. For injury analysis, evaluation timing (WAE or WAT) was considered a repeated-measure variable that allowed comparisons across evaluations taken on the same plot over the same interval (Gbur et al. 2012). An autoregressive first-order covariance structure (AR1) was applied to account for the temporal correlation between repeated measurements taken at different evaluation timings on the same plot (Hamilton 1994; Kiss et al. 2021). In the GLMM models for injury, fluridone rate and evaluation timing were considered fixed effects, and block was treated as a random effect. For models for the other variables, only fluridone rate was considered a fixed effect, and block was considered a random effect. Q-Q plots were used to check the fitness of the model, and final models were selected based on Akaike information criterion values.

Analysis of variance was performed using Type III Wald chi-square tests with the CAR package (Fox and Weisberg 2019). Following the ANOVA, treatment-estimated marginal means (Searle et al. 1980) were calculated using the EMMEANS package (Lenth 2022). The MULTCOMP package (Hothorn et al. 2008) generated a compact letter display to distinguish significant differences among treatments. Estimated marginal means included post hoc Tukey HSD (α = 0.05) adjustments, and the compact letter display was generated via the *multcomp:cld* function.

Results and Discussion

Preemergence Experiments

Visible injury to rice never exceeded 24% in 2022 when fluridone was applied preemergence (Tables 2, 3, and 4). In 2023, most cultivars displayed lower injury levels at 2 and 4 WAE compared with 6 WAE (Table 4). The cultivars CLL15, CLL16, Diamond,

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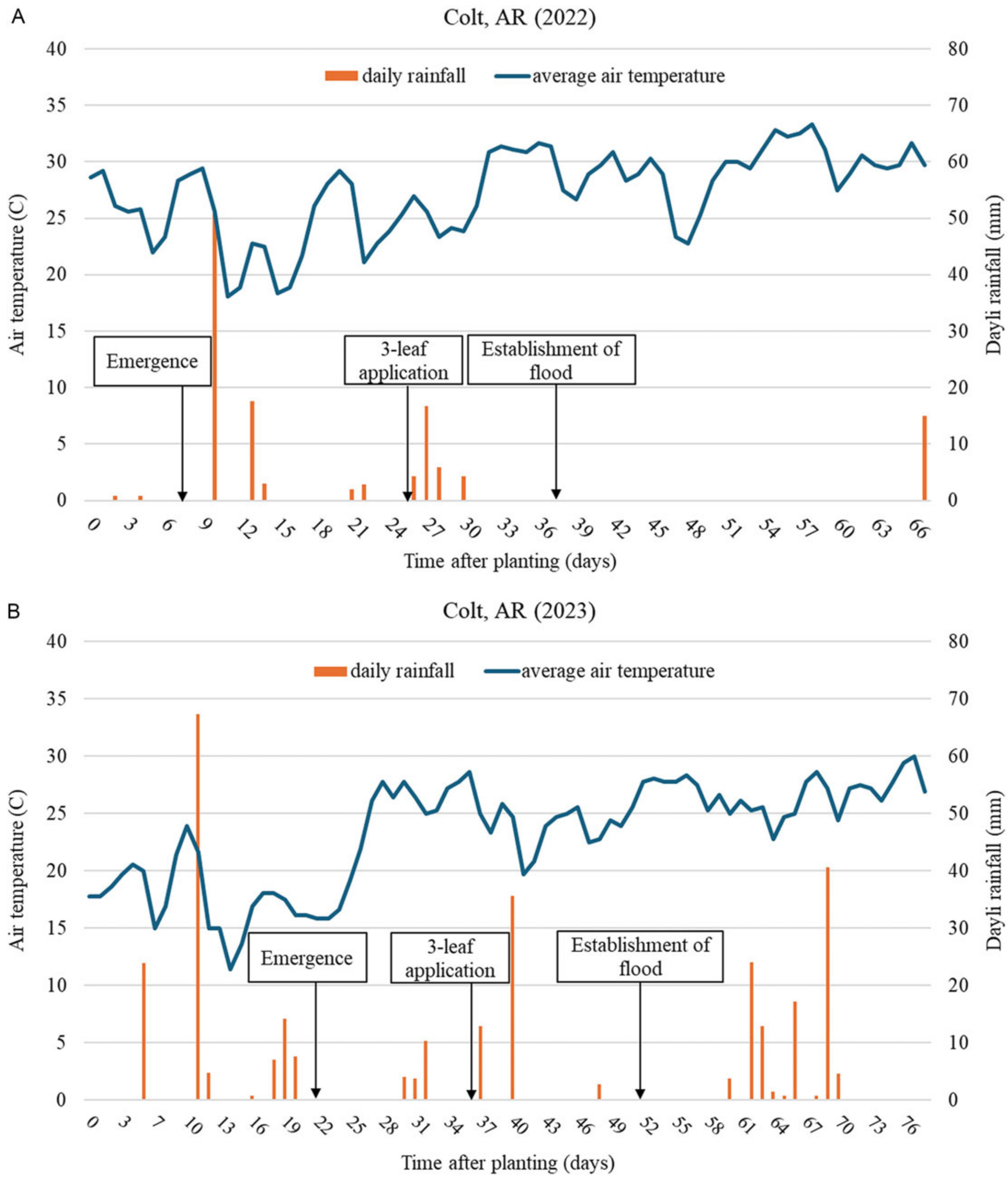

Figure 1. Daily results of observed accumulated rainfall (mm) and air temperature (C) over a 24-h period from the day of planting until the last day of rice injury evaluation in Colt, AR, from 2022 and 2023.

Jupiter, RTv7231 MA, and Titan displayed less than 10% injury regardless of fluridone rate at the first two evaluation timings in 2023. At 6 WAE in 2023, injury levels of at least 30%, averaged over rates, were observed on the cultivars CLL15, DG263L, PVL02, and RT7321FP, with DG263L'displaying 58% injury. These results lead to the suggestion of increased herbicide availability with the establishment of the flood, which occurred 7 wk after planting (4 WAE), resulting in increased injury for most of the cultivars, especially in 2023. Similar results were observed by Martin et al. (2018), when rice injury increased after flood establishment following a preemergence application of fluridone at 224 g ai ha^{-1} on Dewitt and Calhoun silt loam soils.

The lack of an increase in visible injury after the establishment of the flood in 2022 may have been influenced by environmental conditions such as higher temperatures, which may have enhanced herbicide detoxification (Figure 1). Similarly, results reported by Bond and Walker (2011) suggest that imazamox metabolism in treated rice plants was reduced by cooler temperatures, higher rainfall, and lower solar radiation, leading to a yield penalty. Furthermore, rice emergence occurred 7 and 20 d after planting in 2022 and 2023, respectively (Figure 1). The delayed emergence in 2023 may be attributed to lower temperatures after planting (Figure 1; Mertz et al. 2009); however, the cool, wet conditions that existed did not increase injury prior to flood establishment that year in most cultivars. These results are different from those observed in other research with herbicides such as clomazone (Jordan et al. 1998; O'Barr et al. 2007).

Carotenoids are essential in the photosynthetic process, with one function being the protection of chlorophyll from photooxidation (Anderson and Robertson 1960; Sandman et al. 1991).

Table 5. Rice shoot density, groundcover, chlorophyll content, heading date, and rough rice yield as influenced by the main effect rate by year following preemergence applications of fluridone.[a,b,c,d]

		2022					2023				
Cultivar	Rate	Shoot density	Groundcover	Chlorophyll content	Heading date	Yield	Shoot density	Groundcover	Chlorophyll content	Heading date	Yield
	g ai ha^{-1}	plants m^{-1}	%	SPAD	days delayed	kg ha^{-1}	plants m^{-1}	%	SPAD	days delayed	kg ha^{-1}
CLL15	0	56 a	100	35	–	8,920 a	34	100 a	43 a	–	8,010 a
	168	49 ab	100	35	3	9,560 a	36	92 b	11 b	2	4,100 b
	336	46 b	100	34	5	7,300 b	33	93 b	19 b	3	6,890 ab
	P-value	**0.0004**	0.5943	0.8457	0.1614	**<0.0001**	0.6480	**0.0306**	**<0.0001**	0.0833	**0.0045**
CLL16	0	55 a	100	33	–	10,270	32	99	37 a	–	8,030
	168	50 ab	100	33	−1 b	10,050	34	99	28 b	2	7,930
	336	46 b	100	33	3 a	9,750	34	98	26 b	2	7,210
	P-value	**<0.0001**	0.2385	0.8609	**0.0015**	0.3801	0.8127	0.0557	**<0.0001**	0.2207	0.6062
DG263L	0	53	99	34	–	11,470 a	24 a	95 a	29 a	–	9,900 a
	168	52	99	33	0 b	11,060 a	23 a	94 a	20 ab	3 B	6,850 b
	336	51	98	33	2 a	5,360 b	19 b	86 b	14 b	5 A	7,590 b
	P-value	0.8043	0.4126	0.1428	**0.0023**	**<0.0001**	**<0.0001**	**0.0008**	**<0.0001**	**<0.0001**	**<0.0001**
Diamond	0	47	95 a	38	–	10,160	31	97	40 a	–	9,950
	168	47	92 a	37	−2	11,000	28	98	40 a	0	9,880
	336	47	85 b	36	1	9,670	27	96	26 b	0	9,110
	P-value	0.9960	**0.0317**	0.0515	0.1456	0.1614	0.2283	0.3211	**<0.0001**	0.1930	0.5270
Jupiter	0	55	99 a	35	–	9,920 a	18 a	92	44 a	–	7,450 a
	168	48	98 a	35	0 b	9,370 a	18 a	92	44 a	0 b	6,680 a
	336	45	84 b	36	2 a	6,970 b	15 b	87	32 b	2 a	3,940 b
	P-value	0.2474	**<0.0001**	0.5459	**<0.0001**	**0.0398**	**0.0050**	0.4462	**<0.0001**	**<0.0001**	**0.0049**
Lynx	0	43 a	97 a	34	–	11,070 a	–	–	–	–	–
	168	39 ab	96 a	36	3	10,800 a					
	336	34 b	85 b	36	1	6,070 b					
	P-value	**0.0076**	**<0.0001**	0.5258	0.3239	**<0.0001**					
PVL02	0	51	98	33	–	9,520	36 a	97 a	35 a	–	8,230 a
	168	52	100	32	1	8,890	35 ab	94 ab	40 a	0	6,100 ab
	336	49	97	32	2	9,320	28 b	91 b	24 b	1	5,170 b
	P-value	0.8482	0.4131	0.2616	0.3458	0.3111	**0.0052**	**0.0098**	**<0.0001**	0.3672	**0.0023**
RT7321 FP	0	32 a	100	34	–	16,010 a	19	98 a	39 a	–	11,310 a
	168	27 b	100	36	0	14,690 ab	17	87 b	14 b	1	10,940 ab
	336	27 b	100	34	0	11,850 b	17	98 a	21 b	0	10,250 b
	P-value	**0.0013**	0.9520	0.1653	0.0963	**0.0006**	0.0565	**0.0096**	**<0.0001**	0.1134	**0.0009**
RT7521 FP	0	38 a	100	36	–	14,010 a	24 a	99	38 a	–	14,700 a
	168	36 b	100	38	0 b	13,350 ab	20 b	99	36 a	1	13,270 ab
	336	35 b	100	35	4 a	10,420 b	20 b	98	24 b	3	11,970 b
	P-value	**<0.0001**	0.1939	0.2048	**<0.0001**	**0.0017**	**0.0002**	0.3848	**<0.0001**	0.1244	**0.0099**
RTv7231 MA	0	40	100	36	–	12,040	29	99	36	–	12,370 a
	168	43	100	36	0	12,140	29	99	32	0	9,490 b
	336	40	100	36	1	10,250	30	98	27	0	9,040 b
	P-value	0.0751	0.1023	0.6175	0.1573	0.1044	0.7737	0.4863	0.0882	0.9888	**<0.0001**
Titan	0	60	99 a	38 ab	–	10,030 a	32	98	43 a	–	7,540
	168	60	100 a	37 b	−3	10,010 a	30	99	41 a	0	8,200
	336	60	94 b	39 a	−1	7,030 b	30	99	27 b	0	7,390
	P-value	0.9423	**0.0001**	0.0680	0.2963	**0.0005**	0.2936	0.4268	**<0.0001**	0.7184	0.1710
XP753	0	42 a	100	35	–	15,660 a	22	99 a	40 a	–	14,590 a
	168	38 ab	100	35	0	15,780 a	19	98 a	38 a	0 b	14,560 a
	336	36 b	99	34	2	12,830 b	19	95 b	25 b	3 a	12,520 b
	P-value	**0.0003**	0.0785	0.7842	0.1944	**<0.0001**	0.0525	**<0.0001**	**<0.0001**	**<0.0001**	**0.0243**

[a]SPAD is a soil plant analysis development value, an indirect estimate of chlorophyll content.
[b]Bold P-values indicate statistical significance at α = 0.05.
[c]Means within a column followed by the same letter are not different according to Tukey's HSD (α = 0.05).
[d]Dashes (–) represent a delay in heading of zero for the control.

Table 6. Rice cultivar injury as influenced by rate and evaluation timing interaction by year following fluridone applications at the 3-leaf stage.[a,b,c,d]

Cultivar	Rate	2022			2023		
		2 WAT	4 WAT	6 WAT	2 WAT	4 WAT	6 WAT
	g ai ha^{-1}	%					
CLL15	168	1	1	0	0	2	3
	336	1	1	1	2	13	12
	P-value		0.7039			0.5987	
CLL16	168	1	0	0	0	4	2
	336	1	0	1	2	12	11
	P-value		0.5331			0.2933	
DG263L	168	1	1	1	0	22	32
	336	3	2	10	1	38	45
	P-value		0.3237			0.8293	
Diamond	168	2 bc	1 cd	0 d	1	8	5
	336	3 b	4 ab	8 a	2	18	18
	P-value		**<0.0001**			0.2283	
Jupiter	168	2	1	3	0	11	4
	336	3	5	9	2	24	15
	P-value		0.2486			0.2479	
Lynx	168	1	3	5	–	–	–
	336	2	5	11			
	P-value		0.9084				
PVL02	168	1	1	1	1	15	20
	336	1	1	4	6	36	44
	P-value		0.3546			0.5179	
RT7321 FP	168	1	1	1	0	7	4
	336	1	1	1	2	20	16
	P-value		0.6770			0.4774	
RT7521 FP	168	1	0	0	1	11	7
	336	1	2	3	1	19	13
	P-value		0.2089			0.9275	
RTv7231 MA	168	0	1	0	1	10	9
	336	1	1	2	4	28	30
	P-value		0.0638			0.9721	
Titan	168	1	1	1	1	8	5
	336	2	5	8	2	19	18
	P-value		0.2987			0.4141	
XP753	168	2	1	1	0	12	9
	336	3	4	2	1	26	21
	P-value		0.5032			0.5468	

[a]Abbreviation: WAT, weeks after treatment.
[b]Bold P-values indicate statistical significance at α = 0.05.
[c]Means within a cultivar by year for the fluridone rate by evaluation timing interaction followed by the same letter are not different according to Tukey's HSD (α = 0.05).
[d]Flood establishment occurred 4 wk after emergence in both years.

When carotenoid biosynthesis is interrupted, chlorophyll undergoes photooxidative destruction. Therefore, if injury occurs following a pigment-inhibiting herbicide application such as fluridone, a decrease in chlorophyll content is likely to happen, leading to a reduction in the photosynthetic rate (Buttery and Buzzell 1977). The injury caused by fluridone treatments in 2022 did not cause a decrease in the chlorophyll content for any cultivar (Table 5). Conversely, except for the RTv7231 MA cultivar, chlorophyll content decreased in all cultivars in 2023, mostly due to applications of the 2× label rate.

Although most cultivars displayed injury levels below 20% in 2022 (Tables 2, 3, and 4), there was a shoot density decrease in CLL15, CLL16, Lynx, RT7321 FP, RT7521 FP, and XP753 cultivars, primarily caused by the 2× rate (Table 5). The decrease in shoot density among these cultivars was reflected in the groundcover data only for the cultivar Lynx at 8 WAE. However, Diamond, Jupiter, and Titan cultivars experienced a reduction in groundcover, even though no reduction in shoot density was detected (Table 5). In 2023, shoot density was reduced due to fluridone treatments only in the cultivars DG263L, Jupiter, PVL02, and RT7521 FP. As in 2022, cultivars that displayed a reduction in groundcover did not necessarily experience a decrease in shoot density. Groundcover reduction occurred in the cultivars CLL15, DG263L, PVL02, RT7321 FP, and XP753. Groundcover is a good predictor of crop yield (Donald 1998); consequently, a significant reduction in groundcover would likely result in reduced rice yield. Butts et al. (2024) observed that fluridone applications to 3-leaf rice on a precision-leveled field resulted in a decrease of approximately a 45 percentage points in groundcover 10 wk after application at 340 g ai ha^{-1}. The study also demonstrated that although the rice recovered and achieved a similar canopy to the nontreated by 13 wk after application, yield was still negatively affected.

The delay in reaching 50% heading was no more than 5 d relative to each control in both years (Table 5). Eight cultivars exhibited a yield decrease of at least 18% due to the 2× label rate treatment compared with their respective controls in 2022. Fluridone treatments did not affect yield in the cultivars CLL16, Diamond, PVL02, or RTv7231 MA. In 2023, rough rice yields from the CLL16, Diamond, and Titan cultivars were not affected by fluridone treatment. In contrast, there was a yield reduction

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Table 7. Rice cultivar injury as influenced by the main effect rate by year following fluridone applications at the 3-leaf stage.[a,b]

Cultivar	Rate	2022	2023
	g ai ha^{-1}	%	
CLL15	168	1	2
	336	1	9
	P-value	0.5399	0.1460
CLL16	168	0	2*
	336	1	8
	P-value	0.4909	**0.0010**
DG263L	168	1*	18
	336	5	28
	P-value	**0.0203**	0.4419
Diamond	168	1	7*
	336	5	19
	P-value	**0.0296**	**0.0223**
Jupiter	168	2*	5*
	336	6	14
	P-value	**0.0194**	**0.0055**
Lynx	168	3	–
	336	6	–
	P-value	0.5077	–
PVL02	168	1	12*
	336	2	29
	P-value	0.6488	**0.0005**
RT7321 FP	168	1	4*
	336	1	13
	P-value	0.5978	**0.0011**
RT7521 FP	168	0	6
	336	2	11
	P-value	0.3436	0.5443
RTv7231 MA	168	0	7*
	336	1	21
	P-value	0.4789	**0.0409**
Titan	168	1	5*
	336	5	13
	P-value	0.1040	**0.0184**
XP753	168	1	7*
	336	3	16
	P-value	0.5173	**0.0141**

[a]Bold P-values indicate significance at α = 0.05 based on pairwise comparisons.
[b]Asterisk (*) indicates a difference between fluridone rates averaged over weeks after emeregence within the same column for each cultivar by year when interaction is not present.

Table 8. Rice cultivar injury as influenced by the main effect application timing by year following fluridone applications at the 3-leaf stage.[a,b,c,d,e]

	Application timing					
	2022			2023		
Cultivar	2 WAT	4 WAT	6 WAT	2 WAT	4 WAT	6 WAT
	%					
CLL15	1	1	1	1 b	8 a	8 a
P-value		0.4983			**0.0369**	
CLL16	1	1	1	1 b	8 a	7 a
P-value		0.0875			**<0.0001**	
DG263L	2	2	6	1 b	30 a	39 a
P-value		0.8035			**<0.0001**	
Diamond	3	3	4	2 b	13 a	12 a
P-value		**0.0008**			**<0.0001**	
Jupiter	3 b	3 b	6 a	1 c	18 a	10 b
P-value		**0.0033**			**<0.0001**	
Lynx	2	4	8	–	–	–
P-value		0.0784				
PVL02	1	1	3	4 b	26 a	32 a
P-value		0.2713			**<0.0001**	
RT7321 FP	1	1	1	1 c	14 a	10 b
P-value		0.9685			**<0.0001**	
RT7521 FP	1	1	2	1 b	15 a	10 a
P-value		0.5612			**<0.0001**	
RTv7231 MA	0	1	1	3 b	19 a	20 a
P-value		0.3310			**0.0002**	
Titan	2	3	5	2 b	14 a	12 a
P-value		0.6645			**<0.0001**	
XP753	3	3	2	1 c	19 a	15 b
P-value		0.3222			**<0.0001**	

[a]Abbreviation: WAT, weeks after treatment.
[b]Bold P-values indicate significance at α = 0.05.
[c]Means within the same row for each cultivar by year followed by the same letter are not different according to Tukey's HSD (α = 0.05).
[d]When interaction is present, means for the main effect evaluation timing is not separated by letters.
[e]Flood establishment occurred 4 wk after emergence in both years.

ranging from 9% to 49% by all other eight cultivars compared with each control. Among the cultivars that experienced a yield loss in 2023, CLL15 had a yield penalty exclusively from the 1× label rate, DG263L and RTv7231MA had yield decreases at both rates, and the other cultivars experienced a yield reduction only from the 2× label rate treatment. Similar to the other variables analyzed, the differences in yield reduction between years were likely due to varying environmental conditions, as yield reductions at the 1× label rate occurred only in 2023.

The cultivars CLL15, DG263L, Jupiter, RT7321 FP, RT7521 FP, and XP753 suffered yield penalty in both years. Conversely, CLL16 and Diamond did not experience a yield penalty at either rate in both years, suggesting that these two cultivars are highly tolerant to fluridone when applied preemergence. Besides the cultivar PVL02 in 2022, all other cultivars in both years were negatively affected by fluridone on at least one of the variables tested (visible injury, shoot density, groundcover, chlorophyll content, or delayed heading). Among the cultivars for which there was a yield penalty, no single factor consistently contributed to the yield reduction. Therefore, none of the evaluated variables can be used individually to predict the likelihood of yield loss.

A preemergence application of fluridone leads to translocation of the herbicide to the leaves, resulting in bleaching and chlorosis in susceptible plants (Sandmann et al. 1991; Waldrep and Taylor 1976). In nonsensitive species, fluridone tolerance is conferred by limited herbicide translocation from the roots to the shoots, as is the case with cotton (Berard et al. 1978). In a study exposing transplanted plants in a solution containing ^{14}C-labeled fluridone, the herbicide translocated more rapidly to rice shoots than to those of corn (*Zea mays* L.), cotton, and soybean [*Glycine max* (L.) Merr.], indicating that rice is more susceptible than these species (Berard et al. 1978). Additionally, Waldrep and Taylor (1976) reported that fluridone is more effective when applied preemergence than when applied to the foliage, and higher injury levels would be expected to occur at this application timing. Therefore, the cultivars evaluated in this study that did not exhibit yield penalty following a preemergence application of fluridone are likely tolerant to this herbicide.

Postemergence Experiments

Fluridone applied at the 3-leaf rice growth stage caused no more than 11% injury to any cultivar in 2022 (Tables 6, 7, and 8). In 2023, all cultivars experienced greater injury at 4 and 6 WAT, averaged over fluridone rate, compared with the first evaluation (Table 8). At 2 WAT, injury never exceeded 6%. However, by 6 WAT, injury levels ≥20% occurred in the cultivars DG263L, PVL02, and

Table 9. Groundcover, chlorophyll content, heading date, and rough rice yield as influenced by the main effect of rate by year following fluridone applications at the 3-leaf rice stage.[a,b,c,d]

		2022				2023			
Cultivar	Rate	Groundcover	Chlorophyll content	Heading date	Yield	Groundcover	Chlorophyll content	Heading date	Yield
	g ai ha^{-1}	%	SPAD	days delayed	kg ha^{-1}	%	SPAD	days delayed	kg ha^{-1}
CLL15	0	99	34	–	9,060	99	41	–	7,920 a
	168	100	35	2	8,630	99	44	1	8,280 a
	336	100	34	2	9,590	99	36	1	5,880 b
	P-value	0.1400	0.1724	0.8690	0.2927	0.1010	0.0994	0.9752	**<0.0001**
CLL16	0	100	32	–	10,370	100	41 a	–	8,170
	168	100	33	−1	9,340	99	42 a	0	7,670
	336	100	34	0	10,330	100	36 b	−1	7,730
	P-value	0.2921	0.2677	0.5201	0.1550	0.1138	**0.0283**	0.2059	0.6629
DG263L	0	100 a	30	–	10,800	97 a	35 a	–	12,440 a
	168	100 a	30	0 B	11,010	93 ab	18 b	1	9,700 b
	336	99 b	31	1 A	9,720	84 c	17 b	3	7,000 c
	P-value	**<0.0001**	0.4086	**0.0005**	0.0911	**0.0004**	**<0.0001**	0.0909	**<0.0001**
Diamond	0	97	37 a	–	9,520	95	43 a	–	10,660
	168	96	35 b	−1	10,020	95	36 b	0	9,560
	336	94	34 b	1	9,190	96	28 c	2	9,410
	P-value	0.4211	**<0.0001**	0.4049	0.4518	0.6070	**<0.0001**	0.5360	0.0656
Jupiter	0	99	36	–	10,320	92	45 a	–	8,220 a
	168	99	36	0	9,600	92	32 b	1	6,690 ab
	336	99	34	0	9,580	88	24 c	1	5,380 b
	P-value	0.4836	0.5075	0.6834	0.8706	0.4462	**<0.0001**	0.8174	**0.0127**
Lynx	0	100	35	–	10,090	–	–	–	–
	168	100	36	0	10,070				
	336	100	35	0	10,040				
	P-value	0.1847	0.4288	0.6985	0.9946				
PVL02	0	99	31	–	11,170	98 a	40 a	–	8,310 a
	168	100	30	0	10,840	96 a	33 b	2	6,650 a
	336	100	30	0	11,160	85 b	22 c	4	4,690 b
	P-value	0.4137	0.3109	0.9901	0.1723	**<0.0001**	**<0.0001**	0.4328	**<0.0001**
RT7321 FP	0	100	32	–	12,640	100	39 a	–	10,420 a
	168	100	33	0	12,220	99	37 a	0	9,410 ab
	336	100	32	0	12,770	100	20 b	0	8,080 b
	P-value	0.3890	0.1779	0.5465	0.6454	0.3014	**<0.0001**	0.7353	**0.0022**
RT7521 FP	0	100	35	–	14,710	100	39 a	–	14,580 a
	168	100	37	1	15,580	99	35 a	1	11,280 b
	336	99	35	0	14,130	99	21 b	1	11,190 b
	P-value	0.2073	0.0597	0.4347	0.1105	0.1671	**<0.0001**	0.2475	**0.0002**
RTv7231 MA	0	100	34	–	11,750	99	40 a	–	12,300 a
	168	100	35	0	11,620	99	38 a	0	10,500 a
	336	100	33	1	11,060	99	26 b	0	7,080 b
	P-value	0.2331	0.3499	0.2207	0.4852	0.8727	**0.0001**	0.6038	**<0.0001**
Titan	0	100	37	–	8,495	99	43 a	–	8,690 a
	168	100	37	0	8,970	99	29 b	2	8,650 a
	336	100	37	0	8,480	99	20 c	0	5,810 b
	P-value	0.7027	0.9656	0.1696	0.2469	0.0598	**<0.0001**	0.3059	**<0.0001**
XP753	0	100	34	–	16,130	99	40 a	–	14,130
	168	100	35	0	14,730	99	27 b	0	13,010
	336	100	34	0	13,840	99	19 c	2	12,590
	P-value	0.3493	0.7996	0.8174	0.3458	0.1959	**<0.0001**	0.0961	0.2526

[a]SPAD is soil plant analysis development value, an indirect estimate of chlorophyll content.
[b]Bold P-values indicate statistical significance at $\alpha = 0.05$.
[c]Means within a column followed by the same letter are not different according to Tukey's HSD ($\alpha = 0.05$).
[d]Dashes (–) represent a delay in heading of zero for the control.

RTv7231 MA, with 39%, 32%, and 20% injury averaged over fluridone rates, respectively. The other cultivars exhibited no more than 15% injury on the last evaluation. As reported in the preemergence experiment, the increase in rice injury in some cultivars in 2023 may be attributed to the flood establishment, which likely enhanced herbicide availability and consequently increased rice injury. In a similar study, an increase of 19 percentage points in rice injury was observed at 4 WAT compared with 1 WAT following a fluridone application at 340 g ai ha^{-1} at the 3-leaf rice growth stage on a Sharkey-Steele clay soil, which was likely due to the initiation of irrigation (Butts et al. 2024). In the same study, rice was injured 65% at 8 WAT.

Given the minimal injury in 2022, out of the 12 cultivars tested, only Diamond exhibited a reduction in chlorophyll content (Table 9). In contrast, the only cultivar in which chlorophyll content was not decreased in 2023 was CLL15. A reduction in groundcover at 8 WAE occurred to the cultivar DG263L in both years, while groundcover in PVL02 was decreases only in 2023

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(Table 9). No other cultivar's groundcover was negatively affected by fluridone. Furthermore, a delay of no more than 4 d in reaching 50% heading was observed compared with control plants.

Given that a fluridone application at the 3-leaf rice stage is labeled for use at the 1× label rate, which was tested in this study (US EPA 2023), no yield penalty should be expected from herbicide treatment at that rate. Minimal injury levels and few reductions in groundcover, chlorophyll content, and little or no delay in heading caused by fluridone treatment were observed in 2022 (Table 6). Consequently, no yield penalty was observed. In 2023, eight cultivars exhibited a yield penalty, primarily due to the 2× label rate of fluridone. However, only DG263L and RT7521 FP cultivars exhibited a yield reduction following the 1× label rate treatment, and language concerning the sensitivity and risk of yield loss of these cultivars should be applied to the existing label. Similarly, a yield reduction following fluridone application of 340 g ai ha^{-1} at the 3-leaf stage on a precision-leveled field has been reported, with the cultivar RT7521 FP showing a 21% yield penalty (Butts et al. 2024).

Considering the high injury level displayed by DG263L (up to 32%) coupled with the reduction in groundcover and chlorophyll content at the 1× label rate, the yield loss experienced by this cultivar was expected. However, little injury occurred to RT7521 FP, and there was no negative effect in any other variable evaluated at the 1× label rate. Therefore, further research is needed to better understand the tolerance of RT7521 FP to fluridone. Yield from the cultivars CLL16, Diamond, and XP753 was not affected by either rate in either year by fluridone treatment, indicating that these cultivars are tolerant to 1× and 2× of the currently labeled fluridone rates applied at the 3-leaf growth stage.

Practical Implications

The labeling of fluridone for use in rice production offers a new site of action for growers to control annual broadleaf and grass weeds, especially Palmer amaranth. At the labeled rate fluridone can be safely applied to most cultivars of rice at the 3-leaf stage. However, yield loss occurred to DG263L and RT7521 FP when they were treated with the labeled rate of fluridone. Therefore, growers must be careful when choosing which cultivar will receive fluridone if it is going to be a part of the weed management program. Fluridone applications should be avoided in rice fields planted with DG263L and later flooded, and further research is needed to evaluate the tolerance of the cultivar RT7521 FP because it did not exhibit high injury levels (≤11%), but a yield penalty occurred at the labeled rate in one of the years.

Fluridone is highly effective when applied preemergence (Waldrep and Taylor 1976) and is expected to cause more injury to rice when applied at this time. Previous research has suggested that the growth stage at application affects rice cultivar tolerance to herbicides (Bond and Walker 2011, 2012; Wright et al. 2021). Although direct comparisons are not statistically allowed, based on the findings presented here, rice appears to be more tolerant to fluridone when applied at the 3-leaf growth stage than preemergence. Thus, preemergence applications of fluridone to rice should be avoided. Additionally, although the label specifies a zero-day plant-back interval (US EPA 2023), rice should not be replanted in fields treated with fluridone immediately after application. Additional research is needed to determine the most appropriate rice plant-back interval following fluridone application for label clarification. Moreover, the lack of a labeled preemergence application and tolerance of the crop to fluridone applied preemergence complicates Palmer amaranth management because residual control is provided by fluridone, meaning an alternative option would be needed for weeds that have emerged by the 3-leaf stage of rice.

Furthermore, environmental conditions likely substantially affect the degree of crop response from fluridone based on visible injury, shoot density, chlorophyll content, and yield assessments reported here. Cool, wet conditions, more extreme than those tested here, may further increase the extent of injury to rice from postemergence application; however, delaying a fluridone application until the 3-leaf stage of rice should result in warmer conditions than those experienced during crop germination and emergence earlier in the growing season. Additionally, further research is needed to determine the influence of water availability on rice tolerance to fluridone under different water management techniques, such as furrow irrigation, which lacks flooding in most of the field, and alternating wetting and drying where flooding occurs intermittently.

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